Dynamics of hyperon–antihyperon production [1,2]

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Abstract. The dynamics of the strangeness-exchange reactions $\bar{\mathrm{p}}\mathrm{p} \to \bar{\Lambda}\Lambda$, $\bar{\Lambda}\Sigma$ or $\bar{\Sigma}\Sigma$ is discussed, either at the hadron level, in terms of strange-meson exchange, or at the quark level, in terms of quark–antiquark creation or annihilation.

INTRODUCTION

The strangeness-exchange reactions $\bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{Y}}\mathrm{Y}'$, where Y is an hyperon Λ or Σ, have been studied at LEAR by the PS185 collaboration, at several values of the beam momentum. The last runs benefitted from a transversely-polarized target, giving access to a variety of spin observables.

The results of this experiment had a large impact on our community, as seen from the impressive number of articles devoted to these reactions in recent years. It is unfortunately impossible to account here for all contributions. We refer to a recent review article [1] for a more comprehensive bibliography.

Schematically, there are two kinds of approaches. The first one describes $\bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{Y}}\mathrm{Y}'$ by suitable exchanges of mesons, generalizing what is done rather successfully for the long- and medium-range part of the nucleon–nucleon and antinucleon–nucleon interaction.

The second approach is guided by the phenomenology developed to describe the hadron spectrum, the strong decays of hadron resonances, and the Okubo–Zweig–Iizuka (OZI) rule in terms of constituent quarks.

Both pictures describe the main features of the strangeness-exchange reactions, provided they are supplemented by a realistic treatment of the initial- and final-state interaction. However, they differ somehow on their predictions for the spin observables.

HADRONIC PICTURE

In the conventional theory of nuclear forces, the nucleon–nucleon interaction is mediated by the exchange of mesons. Each exchange has a rather clear signature, linked to the quantum numbers of the meson. For instance, a pseudoscalar exchange gives a spin-spin and a tensor components, while the exchange of vector mesons is the main source of

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spin-orbit forces. Isovector exchanges give contributions of different sign and strength to the isospin $I = 1$ and $I = 0$ channels. This means that a detailed analysis of spin observables and a comparison of proton–proton and neutron–proton data can probe the meson-exchange models. Years of measurements with polarized nucleon beams and targets have led to a good understanding of the long- and medium-range parts of the nucleon–nucleon interaction.

It is thus natural to extend this picture to other processes. Fermi and Yang [2], in particular, pointed out that the meson-exchange potential, in a given isospin channel, remains the same when going from the nucleon–nucleon to the antinucleon–nucleon case if the exchanged meson has G-parity $G = +1$, while it flips sign if $G = -1$. This G-parity rule transforms any theoretical model of nuclear forces into predictions for the long- and intermediate-range parts of the antinucleon–nucleon interaction.

Building an antinucleon–nucleon potential starting from meson exchanges was attempted by several authors, such as Bryan and Philips, Dover and Richard, Kohno and Weise, etc. For references, see, e.g., [1]. This might have been sometimes considered with skepticism, as the cross-sections are dominated by a strong annihilation acting up to about 1 fm. However, the analyzing power and the energy-shifts of the P-state levels of protonium are more sensitive to the external part of the interaction, and are well reproduced by the meson-exchange models.

Of particular interest is the charge-exchange reaction $\bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{n}}\mathrm{n}$. The isospin content of its amplitude, which reads

$$\mathscr{M}(\bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{n}}\mathrm{n}) \propto \mathscr{M}(I = 1) - \mathscr{M}(I = 0) , \tag{1}$$

indicates a likely cancellation of most annihilation components, thus enhancing the role of the exchange of isovector mesons such as π and ρ. This was discussed, e.g., at the LEAR Workshop held at Erice in 1982 [3]. The measurements performed by the PS199 collaboration and its sequel confirmed the role of meson-exchange in $\bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{n}}\mathrm{n}$ at low energy [1].

Is is thus tempting to generalize this approach to include strangeness-exchange, by replacing $\bar{\mathrm{n}}\mathrm{n}$ by $\bar{\Lambda}\Lambda$, or more generally $\bar{\mathrm{Y}}\mathrm{Y}$ or $\bar{\mathrm{Y}}\mathrm{Y}'$, if Y denotes a strange baryon. Hence π exchange becomes K exchange, ρ is replaced by K^*, etc. The dynamics is pictured by the diagram of Fig. 1. A strong tensor force is predicted in this approach,

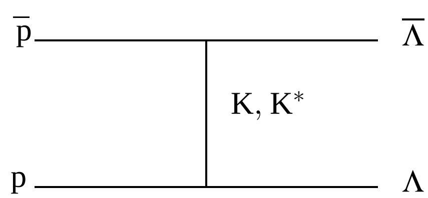

FIGURE 1. Meson-exchange dynamics for $\bar{\mathrm{p}}\mathrm{p} \to \bar{\Lambda}\Lambda$.

as for $\bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{n}}\mathrm{n}$. The latter was unfortunately never probed in detail. Here, thanks to the information provided by the weak decay of $\bar{\Lambda}$ and Λ on the final-state polarization, more observables are available.

Meson-exchange models of $\bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{Y}}\mathrm{Y}'$ have been developed by the Bonn–Jülich group, Furui and Fässler, Tabakin et al., La France et al., among others [1].

QUARK DYNAMICS

Since K or K^* mesons are relatively heavy, the production of hyperons is a rather short-range process and, instead of summing over all possible kaon excitations in the t-channel, one might think of a simple quark process, as pictured in Fig. 2: a pair of ordinary quarks annihilate and a pair of strange quarks is created. Gluons are not shown, but are crucial to actually generate the process.

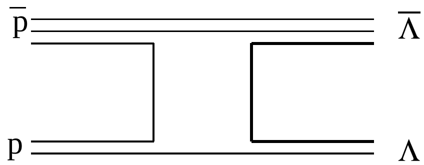

FIGURE 2. Simplest quark diagram for $\bar{\mathrm{p}}\mathrm{p} \to \bar{\Lambda}\Lambda$. The ordinary quarks or antiquarks are shown with thin lines, the strange ones by thick lines.

One should stress once more that these pictures are not Feynman diagrams of a well-defined field theory. They simply describe the flow of flavor from initial to final states. They have to be supplemented by models providing the wave functions to be folded, and operators for quark–antiquark creation or annihilation. There are interesting differences her from an author to another. See, e.g., the review by Alberg [4] for a discussion and references.

In the phenomenology of hadron-resonance decay, it is often assumed that the quark–antiquark pair is created with the quantum numbers of a vacuum, this is the so-called ${}^3\mathrm{P}_0$ model [5]. Other choices are, however, possible, such as ${}^3\mathrm{S}_1$, which would correspond to the quantum numbers of a single gluon, or a superposition of several partial waves.

While PS185 was taking data and seeking further spin observables, new ideas were developed, motivated by experiments on the structure functions of the nucleon. A $s\bar{s}$ pair might be extracted from the nucleon or antinucleon sea instead of being created during the reaction, as schematically pictured in Fig.3 and proposed by Alberg et al. [6], who stressed that a similar mechanism could produce an abundant violation of the OZI rule in annihilation.

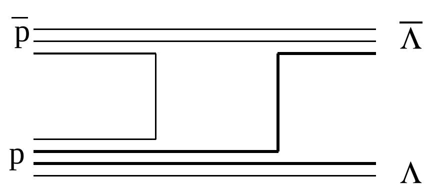

FIGURE 3. Possible sea-quark contribution to $\bar{\mathrm{p}}\mathrm{p} \to \bar{\Lambda}\Lambda$. The strange quarks or antiquarks are shown with thick lines.

MODELS FACING DATA

Though rather different, the meson-exchange and the quark-inspired models gave similar good account of the first PS185 data. In particular, the dominance of the spin-triplet

states over the spin-singlet state was well reproduced. In the nuclear physics approach, this is due to the strong tensor force acting in triplet states and vanishing in singlet. In the quark model of Fig. 2, the light qq and $\overline{qq}$ diquarks having spin 0, and the annihilating $\bar{q}q$ and the created $\bar{s}s$ pairs spin 1, an overall spin triplet is required.

Then it was hoped that more refined spin observables would distinguish among the models. Alberg et al. [6] pointed out that the model of Fig. 3 implies large values for some spin observables, to the extent that the $\bar{s}s$ pair in the initial proton or antiproton is polarized. Holinde et al. [7] made predictions for the spin observables allowed by a polarized target and reached the conclusion that the mechanisms of Fig. 1 and Fig. 2 give significantly different values for some observables.

As shown at this conference, the data came eventually in between the predictions of the meson-exchange and the quark-pair creation models. This means that other effects have to be accounted for. In particular, our knowledge of the initial state is limited, due to the lack of data on spin correlations in elastic $\bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{p}}\mathrm{p}$.

As for the final state, we have basically no information. This is, however, a crucial ingredient for $\bar{\mathrm{p}}\mathrm{p} \to \overline{\Lambda}\Lambda$. La France et al., for instance, had to enforce a very strong annihilation in the $\overline{\Lambda}\Lambda$ channel [8].

PRODUCTION OF Σ

Unlike $\overline{\Lambda}\Lambda$ which filters isospin $I = 0$, the reaction $\bar{\mathrm{p}}\mathrm{p} \to \overline{\Lambda}\Sigma$ (the charge conjugate $\overline{\Lambda}\Sigma$ is implicitely implied) forces an isospin $I = 1$. This means, very likely, differences in the spin-dependence of the initial-state interaction, with less tensor forces, and more spin-orbit. The final state $\overline{\Lambda}\Sigma$ might also differ from $\overline{\Lambda}\Lambda$, with perhaps a slightly weaker annihilation. In a naive quark model, the spin of Λ is carried by the s quark, while the spin of a Σ is opposite to that of its constituent s quark. Hence if the spin correlation in the final state is attributed to a specific state of $\bar{s}s$, it is translated in different effects for $\overline{\Lambda}\Lambda$ and $\overline{\Lambda}\Sigma$.

There are essential differences for $\overline{\Sigma}^+\Sigma^-$ and $\overline{\Sigma}^-\Sigma^+$. In a Yukawa-type of model, the production of the latter can be explained by the exchange of a neutral kaon, and thus the cross-section should be of the same order of magnitude as for $\overline{\Lambda}\Lambda$ and $\overline{\Lambda}\Sigma$. The production of $\overline{\Sigma}^+\Sigma^-$ requires an exotic exchange, namely a mesonic system with one unit of strangeness and two units of charge. It is thus expected to be suppressed. The same difference can be seen in the quark-diagram approach: $\overline{\Lambda}\Lambda$, $\overline{\Lambda}\Sigma$ and $\overline{\Sigma}^-\Sigma^+$ can be reached by annihilating a single $\bar{u}u$ or $\bar{d}d$ pair replaced by an $\bar{s}s$ one. For the final state $\overline{\Sigma}^+\Sigma^-$, the simple quark diagram of Fig. 2 does not operate: one needs more pairs created or annihilated. Holinde et al. [9] found, however, that once all ingredients of their calculation are included, the $\overline{\Sigma}^+\Sigma^-$ production is not too much suppressed.

PRODUCTION OF Ξ

An exotic exchange is also required to produce a $\overline{\Xi}\Xi$ pair. Hence, an anomalous production of $\overline{\Xi}\Xi$ would indicate the possibility of mesonic resonances with strangeness $S = 2$.

There is a long tradition, indeed, coming from duality, to complement the direct investigation of exotic states by an indirect study, which consists of looking at reactions whose tentative mechanism is the exchange of these states. See, e.g., Refs. [10, 11].

If the dynamics of $\overline{\mathrm{p}}\mathrm{p} \to \overline{\Xi}\Xi$ is seen from the s-channel point of view, there are contributions of $\overline{\mathrm{p}}\mathrm{p} \to \overline{\Lambda}\Lambda$ followed by $\overline{\Lambda}\Lambda \to \overline{\Xi}\Xi$. This led Haidenbauer et al. [12] to estimate the cross-section for $\overline{\Xi}^0\Xi^0$ to be significantly smaller than for $\overline{\Xi}^+\Xi^-$. The same hierarchy was found by Kroll et al. [13] in their diquark model, opposite to the earlier estimate by Genz et al. [14].

OUTLOOK

The study of the production of hyperon–antihyperon pairs will hopefully be resumed at the future hadron facilities which have been presented at this conference. The underlying physics is, indeed, related to several important questions of strong-interaction physics, such as the decay of resonances, the violation of flavor SU(3) symmetry, or the validity of the OZI rule.

The charm threshold can be envisaged. Here the contrast should be even more pronounced, between the highly non-perturbative background, and the hard process responsible for $\bar{c}c$ production.

The PS185 experiment clearly demonstrated how useful are spin observables to extract information about the underlying mechanisms. We are now convinced, that if new experiments are once designed to improve our knowledge of antiproton-induced reactions, polarization should be envisaged from the very beginning. If the striking spin effects seen by PS185 have something to do with $\bar{s}s$ creation, this should also show up in other final states with hidden strangeness. Already, important values have been measured for the spin observables of $\overline{\mathrm{p}}\mathrm{p} \to \overline{\mathrm{K}}\mathrm{K}$ [15].

The search for baryonium states was one of the main motivation for building the LEAR facility at CERN and in the design of most LEAR experiments. PS185 was no exception. In the first data, something like a peak was seen in the cross-section of $\overline{\mathrm{p}}\mathrm{p} \to \overline{\Lambda}\Lambda$ as a function of the incoming energy, but the peak was not confirmed in a more detailed scan of the energy-range just above threshold.

The question of baryonium is perhaps not definitely settled. It remains that a very strong attraction is observed between most baryon–antibaryon pairs. Recently, peaks have been seen in the spectrum of baryon–antibaryon states produced in J/ψ decay or B-meson decay. This is the subject of contributions to this conference, see, e.g. ,[16].

The availability of several spin observables for the reaction $\overline{\mathrm{p}}\mathrm{p} \to \overline{\Lambda}\Lambda$ at the same energy stimulated a renewed interest on the methodology required to handle these data. Elchikh et al. [17] addressed the question of testing the compatibility between various observables. Each of them is typically normalized to belong to the interval $[-1,+1]$, but two of them are often restricted to a sub-domain of the square $[-1,+1]^2$, three of them to a sub-volume of the cube $[-1,+1]^3$, etc. This is expressed by inequalities which have to be fulfilled by the experimental values extracted from independent measurements.

More ambitious is the attempt to perform an amplitude analysis of the data. This is implicit in the PS185 analysis [18] and explicit in a recent article by Bugg [19]. The

possibility of extracting unambiguously the amplitudes of a $1/2+1/2 \to 1/2+1/2$ reaction has been often debated. A recent contribution is [20]. In the case of the elastic antiproton–proton scattering, the debate remains open on whether or not the available data are sufficient to determine the five complex amplitudes or the spin-dependent components of the potential. In the case of $\overline{\mathrm{p}}\mathrm{p} \to \overline{\Lambda}\Lambda$, the situation is clearly better since more observables have been measured, and some of these observables are found to be large (in absolute value), thus restricting the range allowed for the yet unknown observables. An amplitude analysis has, indeed, been proposed [19]. Several resonances or resonance-like structures have been identified, which confirm the richness of the $\overline{\mathrm{p}}\mathrm{p} \to \overline{\Lambda}\Lambda$ dynamics, and call for further investigations.

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